Swarm-based Intelligent Routing (SIR) - a New Approach for Efficient Routing in Content Centric Delay Tolerant Networks

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ABSTRACT

This paper introduces Swarm-based Intelligent Routing (SIR), a swarm intelligence based approach used for routing content in content centric Pocket Switched Networks. We first formalize the notion of optimal path in DTN, then introduce a swarm intelligence based routing protocol adapted to content centric DTN that use a publish/subscribe communication paradigm. The protocol works in a fully decentralized way in which nodes do not have any knowledge about the global topology. Nodes, via opportunistic contacts, update utility functions which synthesizes their spatio-temporal proximity from the content subscribers. This individual behavior applied by each node leads to the collective formation of gradient fields between content subscribers and content providers. Therefore, content routing simply sums up to follow the steepest slope along these gradient fields to reach subscribers who are located at the minima of the field. Via real traces analysis and simulation, we demonstrate the existence and relevance of such gradient field and show routing performance improvements when compared to classical routing protocols previously defined for information routing in DTN.

Categories and Subject Descriptors: C.2.2 [Network Protocols]: Routing protocols

General Terms: Algorithms

Keywords: DTN, PSN, CCN, routing protocol, gradient field

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1. INTRODUCTION

Delay Tolerant Networks (DTN) can be considered as a general case of Mobile Ad-hoc NETwork in which there's no assumption of a stable topology. These networks can suffer from partial disconnections which doesn't guarantee the existence of end-to-end paths. Therefore, to communicate, nodes must rely on the store-carry-and-forward paradigm via opportunistic contacts. Information exchange in such type of network makes sense in a wide range of contexts such as spontaneous networks during an event or at workplace, disaster recovery networks, battle field networks, etc.

Nowadays there is more and more interest in content distribution and retrieval for DTN. Indeed, the explosion of the amount of content coupled with the advances of wireless communication technology make that users have more and more tendency to share content via their hand-held devices. In zones where a network infrastructure exists, this can be easily done via classical infrastructure based wireless networks such as WIFI or WIMAX with the underlying economic or access constraints for users. By freeing users from these constraints while offering nearly pervasive communication, DTN or Pocket Switched Networks (PSN) [4] can appear as serious contenders for content delivery if they offer efficient communication techniques. This paper aims to contribute to this issue by introducing a simple and innovative routing protocol adapted to DTN using the *content centric communication*. The content-centric paradigm, initially introduced for wired networks [6], is based on the principle that content should be considered as the first-class network citizens and hence should not be coupled with a reference to the specific physical locations from which that content can be retrieved. This means that network does not have anymore to rely on address allocation and resolution mechanisms that, face to the explosion of the number of devices and their inherent mobility, raise numerous availability, security and location-dependence issues [6]. We call this type of network *Content-Centric Delay Tolerant Networks* or CCDTN.

In this paper, we are interested in defining a routing protocol able to keep track and follow the optimal routes in

CCDTN. Traditionally, content-centric networks follow a publish/subscribe communication scheme. During the first phase, the user interested in a content disseminates his subscription message for that content into the network. When a content provider who published the requested content receives this request, he replies by sending back the content to the subscriber. In the context of DTN where the topology can change rapidly, this message dissemination can be done via simple diffusion mechanisms such as Epidemic routing protocol [13]. But when considering large dynamic networks, these protocols raises scalability issues in term of communication resources (i.e. energy, buffers, bandwidth etc.) or performances (i.e. delay, reliability etc.). Therefore we propose a swarm intelligence based approach for efficient content routing in CCDTN. Swarm intelligence studies the collective “intelligent” behavior of self-organized systems which results from the conjunction of individual decentralized behaviors. Each individual agent in the system follows very simple rules based on its limited knowledge of the local context and doesn’t have any knowledge about the whole system state. However, the sum of interactions between agents leads to the emergence of an intelligent global behavior. This philosophy fits with the context of DTN or PSN because mobile nodes in spontaneous networks usually do not have any knowledge of neither the network topology nor the available global resources. In this networking context, one can consider content routing as an optimization problem in which network nodes, by following simple rules based on local interactions, can find the optimal path to deliver content to users.

The rest of this paper is structured as follows. In Section 2, we formalize the notion of optimal path in DTN. In Section 3, we propose Swarm-based Intelligent Routing (so called SIR) protocol. Section 4 demonstrates the performances of SIR via simulation results. Section 5 reviews the most salient contributions on the issue of routing in DTN. Finally, Section 6 concludes the paper.

2. SHORTEST PATH IN DTN

In a static graph, the classical shortest path problem consists in finding a path between two nodes such that the sum of the weights of its constituent edges is minimal. This definition of shortest path is well suited for static networks but cannot be applied to DTN and dynamic networks in which links between nodes are time varying. Temporal graphs [12], in which a link represents an opportunistic contact at a given instant between two nodes make it possible to model dynamic networks. A path in a temporal graph can be seen as an ordered set of temporal links that allow a message to be transferred using the store-move-forward paradigm between two nodes. Formally, let l_{ij}^{t} be a link between node i and node j at instant t. In consequence, the time ordered set $l_{Ai}^{t_0}, l_{ij}^{t_1}, \ldots, l_{kB}^{t_d}$ constitutes a path from A to B. Note that, because of the links temporal ordering, this definition is asymmetric (i.e. the existence of a path from A to B doesn’t mean there exists a path from B to A). Two metrics can be associated to a dynamic path :

- Delay : the sum of the inter-contact times between consecutive links which constitute the path.

- Number of hops : the number of temporal links which constitute the path.

From these two metrics, two definitions of optimal dynamic path can be derived, depending on the optimization objective. For delay constrained communication the optimal path is the path giving the minimum amount of delay. If there are several paths giving the same delay, then the one giving the minimum number of hops is selected. For resource constrained communication one can consider the optimal to be the path giving the minimum number of hops. In this case, if there are several paths with the same number of hops, the one giving the minimum delay is selected. In the following, we will focus on delay constrained path only, in this case the delay is also called the path length.

3. SWARM-BASED INTELLIGENT ROUTING (SIR)

Leveraging on the definition of shortest path previously introduced, this section will give elements of response to the question “how to maintain information about short routes, if not shortest ones, and how to route efficiently content along these routes in dynamic networks ?”. In order to solve this issue, we introduce *Swarm-based Intelligent Routing (SIR)* a novel routing protocol inspired by the collective swarm intelligence that can emerge from basic individual behaviors applied by each element of a swarm of autonomous agents. In SIR, network nodes, via opportunistic contacts, maintain for each subscription they have heard of an utility function which sums up how close (as defined in Section 2) this node is from a content subscriber. We will show that the distributed set of scalars associated to a given subscription forms across the network a gradient field in which the maximum value is carried by the content provider and the minimum value by the content user. Therefore content routing with SIR simply consists in following the steepest slope towards the minima of the gradient field where content users are located. Such algorithm works in a complete distributed way so that nodes do not need to maintain any knowledge about the global topology of the network.

Following the publish/subscribe paradigm, the SIR routing is composed of two following phases.

3.1 Interest Dissemination Phase

In this phase, nodes register their interest for a content by disseminating efficiently this interest into the network. We leverage on this interest dissemination to dynamically establish a gradient field of which the intensity decreases from the content providers to the content users. The Binary-Spray-and-Wait protocol [11] well known to offer a good trade-off in term of delay, delivery ratio and resources use is selected for the efficient diffusion of subscription messages. In SIR, a relaying node receives not only copies of subscription messages but also a couple of metric values defined in the previous section (i.e. delay and number of hops). SIR relay nodes update their utility values through opportunistic contacts according to theirs and their encounter’s delays and number of hops from the content users, and hence contribute to establish gradient fields that keep track of the shortest path between content producers and content users. Relay nodes utility is updated according to the following behavior:

- If a relay meet a content user, it resets its delay to 0 and updates its number of hops to 1.

- If two relays meet each other, the node with the higher delay sets its delay equal to the delay of the other node and its number of hops equal to the number of hops of the other node plus 1

- If two relays meet each other and have the same delay, then they keep theirs utility values unchanged.

The interest dissemination phase is summarized in Algorithm 1.

Algorithm 1: Interest dissemination algorithm for a SIR relay node

```
/*this.isRelay == true*/;
if encounteredNode = CONTENT_USER(contentID) then
    this.delay(contentID) ← 0;
    this.numberOfHops(contentID) ← 1;
else
    if encounteredNode.isRelay(contentID) = true then
        if this.delay(contentID) ≠
        encounteredNode.delay(contentID) then
            d = min(this.delay(contentID),
            encounteredNode.delay(contentID));
            if d = this.delay(contentID) then
                encounteredNode.delay(contentID) ←
                this.delay(contentID);
                encounteredNode.numberOfHops(contentID)
                ← this.numberOfHops(contentID)+1;
            else
                this.delay(contentID) ←
                encounteredNode.delay(contentID);
                this.numberOfHops(contentID) ←
                encounteredNode.numberOfHops(contentID)
                + 1;
    else
        Share a half of interest message copies;
        encounteredNode.delay(contentID) ←
        this.delay(contentID);
        encounteredNode.numberOfHops(contentID) ←
        this.numberOfHops(contentID) + 1;
        encounteredNode.isRelay(contentID) ← true;
```

3.2 Content Dissemination Phase

When a content publisher receives the interest message, the second phase consists in sending back the content to the user by following ideally a path as close as possible to the shortest path between the content provider and the content user. The Binary Spray and Wait protocol is also used as the underlying diffusion mechanism. The content forwarding decision mechanism consists in always selecting the relay of which the delay is smaller (i.e. a node closer in time to the content user). If the delays are equal, the content is forwarded if the encountered relay has a smaller number of hops (i.e. closer to the content user in space).

4. SIMULATION RESULTS

This section focuses on the simulation-based evaluations of the SIR routing protocol introduced in the previous section. First, we verify the hypothesis that the utility function summarizes the proximity of a node to the content subscriber. Secondly, we run the protocol on real traces and compare the delay of the paths found by SIR with the shortest paths. This makes it possible to assess how close paths taken by SIR are to the shortest path. Finally, we compare the performances of SIR with two classical routing protocols : PROPHET and Spray-and-Wait.

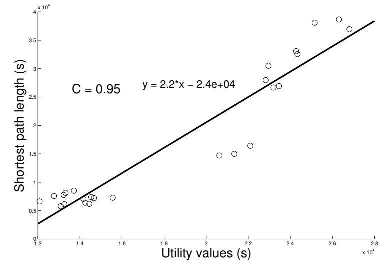


Figure 1: Correlation between the utility values of a node and the shortest path length from that node to the content subscriber

These simulations were realized under our MATLAB-based simulator in which the communication protocol stack is simplified and focus mainly on the network layer. For the sake of simplicity, we also assume that connection between nodes have an infinite bandwidth and nodes have an infinite buffer size. The communication channel is modeled as an unicast channel. When two nodes are in communication range, they exchange instantly their buffers containing interests, contents and utilities.

4.1 Consistency of the Utility Function

As introduced in the previous section, the utility function is supposed to sums up the proximity of a node to the content subscriber. If this makes sense, there must have a linear relationship between the utility value and the shortest path length. To verify this hypothesis, we ran SIR on Infocom2005 traces [4] which record bluetooth connectivity of 41 handheld devices carried by conference attendees during 3 days. In the selected scenario, one content user sends his interest for this content to one content publisher and then receives the periodically refreshed content from the later. 41 interest message copies initially disseminated into the network allow to establish a gradient field which is maintained and reinforced by all the nodes during the simulation. We measure on one hand the evolution of utility values of all nodes and on the other hand the shortest path length between the content subscriber and all other nodes. We takes then the average value over all nodes. Figure 1 shows the correlation between these two series of values. We can see that these two series of values are highly correlated with a correlation coefficient of 0.95 which reinforces our hypothesis.

4.2 SIR vs Optimal Solution

The goal of this evaluation is to show that by using the gradient field maintained and used by SIR one can achieve a nearly optimal solution. We conduct the same experiment described in the previous section. Then, we measure the content delivery delay of different pairs of user/publisher at different instants of the day. On the other hand, we measure the shortest path between these pairs of nodes. Figure 2 shows the average result over 10 pairs of nodes. These results show that SIR can find paths with delivery delays very close to the optimal path.

4.3 SIR vs Other Protocols

In this section, from a simulation-based point of view, we compare the SIR routing performances with the ones given

Table 1: Simulation Configurations

Number of nodes	100
Number of content subscriber	1
Number of content provider	1
Network size	300×300 m^2
Number of zones	10×10
Duration	10000 s
Warm up	2000 s
Radio range	10 m
Node speed	[3, 5] km/h
Content release frequency	100 s
Number of content copies (for SIR and BSNW)	10

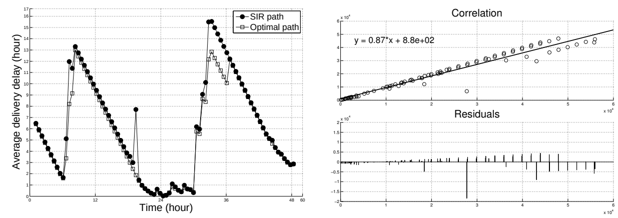
by a basic Binary Spray and Wait (BSNW) protocol and the ones delivered by PROPHET - a probabilistic based routing protocol. The performances delivered by BSNW routing protocol can be considered as floor performances that SIR by extending BSNW with an utility function should overtake in every situation. PROPHET can be considered like a swarm inspired protocol based on a distributed processing of inter-node encounter probability. Therefore the comparison of SIR and PROPHET performances allows to classify our approach in comparison with a probabilistic approach known to perform well in DTN.

In order to reproduce at the simulation level realistic human mobility patterns, we use the STEPS mobility model [8]. As we have shown in a previous contribution, this flexible parametric model can express a large spectrum of mobility patterns : from highly nomadic ones to localized ones, allowing us to evaluate routing protocols in different mobility contexts. In all the following scenarios, the network area is modeled as a torus divided in a number of square zones. Inside these zones, nodes move following the Random Waypoint model. Each node is attached to one preferential zone. The movement of nodes between zones is driven by a parameter of the STEPS model which allows the node's nomadism to be enforced or reduced (i.e. modify the probability that a node moving outside his preferential zone has to return in that zone). Table 1 summarizes the main simulation parameters.

We chose to simulate 3 different scenarios to study the impact of three fundamental factors on the protocols : mobility, connectivity and scalability. In these simulation scenarios, we use the average delivery delay and the average delivery ratio (i.e. the ratio between the number of messages received and the number of messages sent) as performance measures.

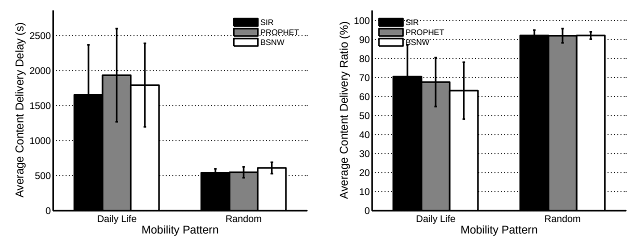
In the first scenario, we run all the protocols under two different mobility contexts : a human daily life one with highly localized nodes and a random one in which nodes move randomly around the network area. Contents are sent periodically by publishers to the subscriber each 100 seconds. The average delivery delay and average delivery ratio are measured between different pairs of nodes and then averaged over 10 simulation runs. The bar plot of these measures are shown in Figure 3. The line on top of each bar represents the 95% confidence interval of the estimated mean value. We can see that in the quite static mobility context, SIR outperforms the other protocols. SIR significantly decreases delivery delay and increases delivery ratio when compared to the two others protocols. Even when considering highly nomadic mobility contexts which tends to reduce the spatio-temporal correlation between nodes, SIR still slightly outperforms the other protocols.

In the second scenario, we perform the same experiment but in place of varying the mobility pattern, we vary the



(a) Evolution over time of the delivery delay (b) Correlation between the delivery delay of SIR and the shortest path length

Figure 2: Delivery delay of SIR vs optimal solution



(a) Impact of mobility on content delivery delay (b) Impact of mobility on content delivery ratio

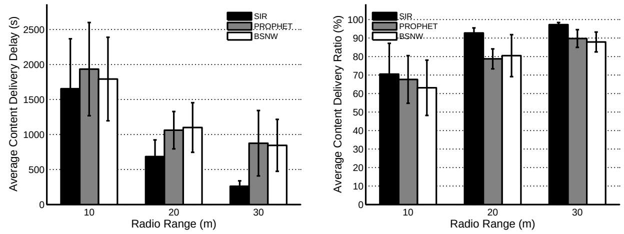
Figure 3: Routing performances of all routing protocols under different mobility contexts

connectivity between nodes by increasing their radio range from 10 m to 30 m. Figure 4 shows that SIR outperforms the other protocols in all the contexts. Moreover, in the context with a high range connectivity, which reduces significantly path lengths for all the protocols, SIR still delivers better performances both in term of delay and delivery ratio.

Finally, we test the capacity of SIR to route content efficiently in large scale networks. For this, we increase the number of nodes in the network while keeping the node density constant. As seen on Figure 5, SIR scales well compared to the two other routing protocols, especially to BSNW. This can be intuitively explained by the fact that in large networks, without any supplementary information and with a limited number of content copies, diffusion based protocols such as BSNW fail to relay content to good candidates which would allow the content to reach rapidly the destination. On the contrary, SIR, with the additional routing constraint based on nodes spatio-temporal distance from the destination, improves significantly the routing performances.

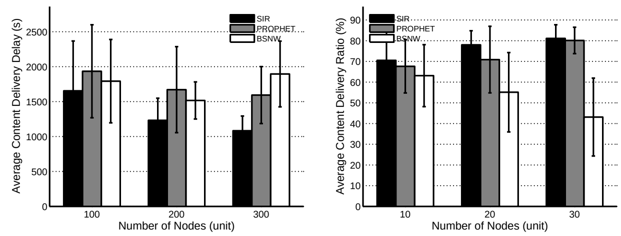
5. RELATED WORKS

Basically, routing protocols for DTN can be divided in two categories : non-context and context-based (see [2] for a survey). The first category consists of protocols in which nodes make forwarding decision while ignoring the network context (i.e. mobility or social structure). Protocols falling into this category belong to flooding and constrained-flooding families such as Epidemic Routing [13] or Spray-And-Wait [11]. In the second category, nodes exploit the context information (e.g. frequency of contact) from their local interactions to find the good candidates to forward messages. PROPHET [7], Bubble Rap [5], HiBOp [1] and Propicman [9] fall into this



(a) Impact of connectivity on content delivery delay (b) Impact of connectivity on content delivery ratio

Figure 4: Routing performances comparison of all routing protocols under varying connectivity level



(a) Content delivery delay in function of number of nodes (b) Content delivery ratio in function of number of nodes

Figure 5: Scalability of all routing protocols

category. However, these protocols are always rooted in the end-to-end paradigm and not adapted to content-centric communication.

Attempts to bring the content-centric paradigm to opportunistic networks include SocialCast [3] and TACO-DTN [10]. By resting on two universal and simple metric values intrinsic to the evolution of every networks (i.e. space with the number of hops and time with the delay) SIR distinguishes from these protocol based on more complex and artificial interaction patterns.

Finally, the notion of temporal path length was first addressed in [12] to study the properties of temporal graph . We leveraged on this definition of temporal path length to formalize the notion of shortest path in DTN.

6. CONCLUSION

In this paper, we addressed the issue of efficient routing in content-centric delay-tolerant networks via a novel approach based on swarm intelligence. The routing problem is viewed as an optimization problem in which nodes follow a simple individual rule from which emerges a collective intelligence allowing to find the shortest paths between content producers and content users. We formalized the notion of shortest path in DTN which takes into account two dual metrics : delay and number of hops. We proposed then SIR a simple routing protocol that validates the significance of this type of approach for CCDTN. Simulations with a realistic mobility model show that the proposed protocol, based on the distributed elaboration of gradient fields between content user and content producers, is never outperformed by classical information diffusion mechanisms such as Binary Spray and Wait and probabilistic routing. Moreover SIR increasingly outperforms these protocols when the spatio-temporal correlation between nodes increases. We are convinced that there is still a margin of progress for the processing and actualization of the SIR utility metric by introducing for example inter-contact and intra-contact delays experienced by each node.

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